Late Paleozoic extensional reactivation of the Rheic-Rhenohercynian suture zone in SW England, the English Channel and Western Approaches

*Andrew C. Alexander [1], Robin K. Shail [2] and Brian E. Leveridge [3]

[1] Siccar Point Energy Limited, H1 Building, Hill of Rubislaw, Andreson Drive, Aberdeen AB15 6B

[2] Camborne School of Mines, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Penryn TR10 9FE

[3] 8 Orchard Way, Willand Old Village, Cullompton EX15 2SG (previously British Geological Survey)

*Correspondence (andy.alexander@siccarpointenergy.co.uk)

Reactivation Extension Variscan Rheic Rhenohercynian

Abstract

The Rheic Ocean is a persistent feature of Paleozoic palaeogeographies whose closure contributed to the development of the Variscan orogen and formation of Pangaea. Geological and geophysical data indicate repeated episodes of Paleozoic rifting and plate convergence around SW England and the adjacent offshore areas. SW England occupied a lower plate position during the Devonian-Carboniferous, on the northern passive margin of the short-lived Rhenohercynian Ocean that had formed near a recently closed segment of the Rheic Ocean. Variscan plate convergence resulted in the development of the composite southwards-dipping Rheic-Rhenohercynian suture zone by the latest Devonian and inversion of the lower plate basins during the Carboniferous. Early Permian NNW-SSE extensional reactivation of this suture zone controlled the development of the Western Approaches Basins in its hangingwall and provides an excellent example of Wilson Cycle structural inheritance. The onshore expression of this episode includes shear zones and detachment faults consistent with top-to-the SSE extensional reactivation of Variscan thrust faults. There is a progression to higher-angle brittle extensional faults that cut-out earlier structures. Exhumation of the lower plate was accompanied by Early Permian mantle and concomitant crustal partial melting, the construction of the Cornubian Batholith, and W-Sn-Cu fracture-hosted mineralisation.

(196 words)

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The Rheic Ocean is a persistent feature of Paleozoic palaeogeographies whose closure contributed to the development of the Variscan orogen and formation of Pangaea (e.g. Nance *et al.* 2010; Kroner & Romer 2013; Domeier 2016; Franke *et al.* 2017). In his landmark paper, Wilson (1966) demonstrated that the locus of Atlantic Ocean opening was strongly influenced by the Lower Paleozoic Iapetus suture (Fig. 1). In the Central Atlantic, the Rheic and Iapetus sutures are subparallel and broadly coincident (e.g. Nance *et al*. 2010; Chenin *et al*. 2015), but farther north the Rheic suture zone diverges and passes eastwards into western and central Europe (Fig. 1), via a 400 km long segment typically shown at the southern margin of the Variscan Rhenohercynian Zone, offshore from SW England (e.g. Holder & Leveridge 1986b; Franke 2000; Nance *et al.* 2010; Kroner & Romer 2013). Here, the Rheic-Rhenohercynian suture zone is a composite expression of the Rheic Ocean and the marginal or successor Rhenohercynian Ocean (Franke 2000; Shail & Leveridge 2009; Eckelmann *et al*. 2014; Franke *et al*. 2017).

Whilst Mesozoic North Atlantic opening did not progress in the Western Approaches and western English Channel (e.g. Chenin *et al*. 2015), the Rheic-Rhenohercynian suture zone underwent substantial earlier extensional reactivation during the latest Carboniferous to Early Permian post-Variscan extensional-dextral transtensional regime recognized across most of Europe (Arthaud & Matte 1977; Ziegler & Dèzes 2006; Edel *et al*. 2018). The purpose of this contribution is to demonstrate how these multiple episodes of rifting and plate convergence recorded during the Paleozoic geological evolution of SW England and adjacent offshore areas provide an excellent example of Wilson Cycle inheritance. We describe the Variscan and post-Variscan tectonic and structural development in the context of the lower northern plate (SW England), the Rheic-Rhenohercynian suture zone and the upper southern plate (Normannia/Mid-German Crystalline Rise). We synthesize previous field-based studies (Holder & Leveridge 1986a, b; Shail & Wilkinson 1994; Alexander & Shail 1995; 1996; Shail & Alexander 1997; Hughes *et al*. 2009) with published and new observations and interpretations from offshore seismic, gravity and magnetic data.

The Rheic-Rhenohercynian suture zone

The Rheic Ocean suture (Fig. 1) can be traced from Mexico to Central Europe (Nance *et al.* 2010, 2012; Torsvik & Cocks 2017). It was initially inferred from contrasting Ordovician and Silurian marine faunas in Wales (Avalonia) and Armorica (Cocks & Fortey 1982), and subsequently confirmed by palaeomagnetic data (e.g. Trench & Torsvik 1992).

Opening of the Rheic Ocean initiated during the Early Ordovician on the northern margin of Gondwana, possibly along a Neo-Proterozoic suture, during rifting and separation of Avalonia and other peri-Gondwanan terranes (e.g. Cocks & Torsvik 2006; Murphy *et al.* 2006; Torsvik & Cocks 2017). The subsequent northwards drift of Avalonia and widening of the Rheic Ocean was accompanied by the closure of the Tornquist Ocean in the Late Ordovician, and the Iapetus Ocean during the Silurian, to form the Caledonian Orogen and Laurussia (e.g. Soper *et al.* 1992; Domeier 2016). By the Early Silurian the Rheic Ocean, separating Gondwana from Laurussia, was extensive with a maximum width of *c.* 4000 km (e.g. Nance & Linnemann 2008; Domeier 2016). The northward drift of Gondwana and associated microcontinents (Armorica, Iberia) brought about the ultimate closure of the Rheic Ocean, by subduction and collisional accretion, during the late Silurian to Carboniferous; the commonly inferred position of the Rheic Suture across western Europe is shown in Fig. 2.

The detailed timing of Rheic ocean closure, and the nature and polarity of its associated subduction zones and suture(s) are not fully constrained. A consensus is yet to be reached as to whether Devonian rift-related sedimentation and magmatism in the Variscan Rhenohercynian Zone (Fig. 2), which includes the SW England study area, occurred in a marginal basin north of the Rheic Ocean or in a successor Rhenohercynian Ocean following its latest Silurian-earliest Devonian closure (e.g. Franke 2000; Shail & Leveridge 2009; Eckelmann *et al*. 2014; Von Raumer *et al*. 2016; Arenas *et al*. 2016; Franke & Dulce 2017;

Franke *et al.* 2017). Distinct expressions of the Rheic and Rhenohercynian sutures have been inferred, in the Spessart Mountains (Germany), but the two sutures are generally shown as coincident and described as the Rheic-Rhenohercynian suture zone (Franke 2000; Franke & Dulce 2017; Franke *et al*. 2017). In the following sections, we refer to "lower plate" and "upper plate" with respect to the SE-dipping late Devonian-early Carboniferous Rhenohercynian suture zone that is imaged cutting the whole crust on reflection seismic profiles immediately south of SW England (Leveridge *et al*. 1984; BIRPS & ECORS 1986; Le Gall 1990).

Lower plate – SW England

Pre-Devonian basement

Regions north of the Rheic-Rhenohercynian suture zone typically possess, or are assigned to, Avalonian basement (e.g. Franke 2000; Kroner & Romer 2013; Domeier 2016). However, the pre-Devonian basement of SW England is poorly constrained as the only pre-Devonian lithostratigraphical units are allochthonous and crop out in the Lizard Complex close to the Rheic-Rhenohercynian suture (Fig. 3). Here, tonalitic gneisses of Late Cambrian age (Man O' War Gneiss) and amphibolite facies metasedimentary and metabasic rocks (Old Lizard Head Formation) structurally underlie the mantle peridotites of the Lizard Complex ophiolite (Jones 1997; Sandeman *et al.* 1997; Nutman *et al.* 2001; Clark *et al.* 2003). Similar late Cambrian-Early Ordovician lithostratigraphical units, interpreted to have formed during rifting along the northern margin of Gondwana (e.g. Cocks & Torsvik 2006), occur widely throughout the Variscan orogen. These allochthonous units could have originated from the southern side of the suture and so do not necessarily constrain SW England basement. Xenoliths of foliated granitoid, recorded from Late Devonian syn-rift basalts in the Gramscatho Basin (Fig. 3), do reflect lower plate basement but are undated (Goode & Merriman 1987). Rare inherited Mesoproterozoic and late Devonian zircons in the Early Permian Cornubian Batholith (Neace *et al*. 2016), and Lower Paleozoic zircons in the Palaeocene Lundy Granite (Charles *et al*. 2017), do not provide substantive constraint.

However, there are several indirect lines of evidence that indicate, whilst SW England basement is of peri-Gondwanan provenance (e.g. Cocks & Torsvik 2006), it might not be exclusively Avalonian: (1) εNd values for SW England granites are rather more negative than those for typical Avalonian basement, overlapping with values for Armorica/Saxothuringia (Shail and Leveridge 2009); (2) εNd isotopic signatures of Devonian sedimentary rocks in southern SW England, the South Portuguese Zone and the isotopically more juvenile plutons they host, are similar to those for the Meguma terrane in Nova Scotia (Nance *et al*. 2015); (3) Sr and Nd isotopic compositions of Early Permian lamprophyres and basalts change between northern and southern SW England, approximately corresponding to the southern margin of the Culm Basin; this has been interpreted as the trace of a pre-Devonian terrane boundary, between Avalonia and Armorica, in the lithospheric mantle (Dijkstra & Hatch 2018). In addition, northerly dipping reflectors, tentatively classified as 'Caledonian', have been recognized in the lower crust and mantle below SW England (Bois *et al*. 1990; Le Gall 1990). These data are broadly consistent with the late Silurian accretion of Armorican lithosphere to the southern margin of Avalonia, possibly by N-directed subduction, prior to Early Devonian Rhenohercynian rifting (Franke 2000; Shail & Leveridge 2009; Franke *et al*. 2017) and a wider 'two-stage' collision model for the consolidation of Pangea (Arenas *et al*. 2016).

SW England Devonian-Carboniferous sedimentation + magmatism

The Early Devonian to Carboniferous successions of SW England share a broadly equivalent tectonostratigraphical evolution with other massifs in the Rhenohercynian Zone (Franke & Engel 1982; Holder & Leveridge 1986b; Franke 2000; Franke *et al*. 2017). They document the development of rift basins and a S-facing passive margin that, in the south, records convergence-related sedimentation and ophiolite obduction in the latest Devonian, consistent with a lower plate position relative to the S-dipping Rheic-

Rhenohercynian suture (Leveridge & Hartley 2006; Shail & Leveridge 2009; Leveridge & Shail 2011a). A series of sub-basins have been defined (Leveridge *et al*. 2002; Leveridge & Hartley 2006) (Fig. 3). The Tavy, South Devon and Looe sub-basins correspond to the proximal passive margin in which the continental lithosphere underwent moderate thinning (Leveridge 2011; Whittaker & Leveridge 2011). In contrast, the Gramscatho Basin, whilst largely preserving Late Devonian syn-convergence deep marine sequences, originally formed the distal passive margin where continental lithosphere was substantially thinned and transitioned southwards into the Lizard (Rhenohercynian) oceanic lithosphere (Shail & Leveridge 2009; Leveridge & Shail 2011b). The principal evidence for rift- and convergence-related sedimentation and magmatism is summarised below.

Rift-related sedimentation had commenced by the Early Devonian when the oldest successions in SW England, the ?Lochkovian-Pragian non-marine Dartmouth Group and Pragian shallow marine Meadfoot Group, were deposited in the Looe Basin (Fig. 3) accompanied by contemporaneous rift-related bimodal magmatism (Merriman *et al.* 2000; Leveridge *et al.* 2002). Episodic rifting continued to the Tournaisian, causing the progressive development of the North Devon, South Devon, Tavy and Culm basins, each with a distinct lithostratigraphy (Leveridge *et al.* 2002; Leveridge & Hartley 2006). By the Middle Devonian (Eifelian to Givetian) a shallow marine shelf was established with reef carbonates on highs and mudstones deposited in intervening basins (e.g. Leveridge & Hartley 2006; Leveridge 2011). Farther south, rifting had formed the distal passive margin of the Gramscatho Basin and Lizard oceanic lithosphere (Rhenohercynian Ocean) before the late Emsian (Clark *et al.* 1998a; Cook *et al*. 2000; Nutman *et al*. 2001). Eifelian mudstones, cherts and limestone turbidites (Pendower Formation) rest upon T-MORB pillow basalts in the Veryan Nappe (Leveridge 2008; Leveridge & Shail 2011b). Undated, but presumed Devonian, N-MORB volcanic rocks are recorded from the Start Complex (Fig. 3) (Floyd *et al.* 1993).

Convergence-related sedimentation on the distal passive margin is recorded in the deep marine sequences of the Gramscatho Basin (Fig. 3) (Holder & Leveridge 1986a; Leveridge & Shail 2011b). Its onset is marked in the Veryan Nappe by a change from the Eifelian mudstones, radiolarian cherts and limestone turbidites of the Pendower Formation to ?Givetian-Famennian proximal deep marine sandstones, mudstones and olistostromes of the Carne and Roseland Breccia formations (Holder & Leveridge 1986a; Leveridge *et al.* 1990; Leveridge & Shail 2011b). The Roseland Breccia Formation olistrostomes indicate proximity to an active convergent margin in which both continental and oceanic crust was being re-sedimented in a variety of rock falls, slides and sediment gravity flows (Leveridge 1974; Barnes 1983; Leveridge 2008; Leveridge & Shail 2011b). Large (>100 m diameter) olistoliths of Ordovician quartzite have an Armorican faunal provenance (Sadler 1974) that is consistent with their detrital zircon age populations (Strachan *et al.* 2014). An Armorican provenance is also indicated by zircons derived from the sandstone matrix of presumed Late Devonian deep marine debris flows; an Avalonian provenance component cannot be precluded but characteristic Mesoproterozoic zircons are negligible (Strachan *et al*. 2014). Two granite cobbles from deep marine conglomerates have volcanic arc or syn-collisional geochemical signatures and yield magmatic U-Pb zircon ages of Late Silurian (Ludlow, 422 ± 4 Ma) and Late Devonian (Early Famennian, 373 ± 6 Ma) suggesting derivation from an upper plate magmatic arc developed on older non-Avalonian crust (Dorr *et al.* 1999). In addition, a resedimented sandstone clast with a Late Silurian cleavage has also been recorded (Fitch *et al.* 1984). Sandstone provenance studies also indicate a magmatic arc source (Floyd *et al.* 1991). The uppermost parts of the Roseland Breccia Formation include a resedimented clast of MOR basalt up to 1.5 km in diameter (Leveridge 2008).

Upper Plate – Normannia (Mid-German Crystalline Rise)

The upper plate forms the basement to a large proportion of the offshore post-Variscan sedimentary basins in the western English Channel and Western Approaches (Fig. 2). The Eddystone Gneiss, a garnetiferous granite gneiss, is exposed with schists and other lithologies, in reefs just offshore from SW England (Fig. 3)

(Phillips 1964). Interpretation of reflection seismic profiles and nearshore bedrock mapping (Leveridge *et al.* 1984; Holder & Leveridge 1986a, b; Leveridge 2008) indicates that it forms part of the upper plate Normannian Nappe or 'Normannia', a thrust sheet overlying the Lizard Complex. The Eddystone Gneiss has a Frasnian (382 ± 17 Ma) K-Ar biotite cooling age (Miller & Green 1961) but the protolith age is unknown; it has been correlated with the late Cambrian Man O'War Gneiss and Old Lizard Head Formation in the Lizard Complex (Leveridge 2008).

Farther south, in the southern parts of the Western Approaches Trough and Brittany Basin there are limited pre-Devonian well penetrations (e.g. Lenkett-1 Well, Ruffell *et al.* 1995). These typically indicate rocks that can be correlated with Penteverian and Brioverian sequences from the Armorican Massif in NW France and the Channel Islands that were deformed during the Cadomian orogeny (590-540 Ma) (e.g. D'Lemos *et al.* 1990). Lower Paleozoic (Cambrian-Ordovician) successions in the Armorican Massif record rifting on the northern margin of the Gondwanan plate, consistent with the initiation of the Rheic Ocean (e.g. Matte 1986; Faure *et al.* 2005; Cocks & Torsvik 2006).

In the Melville Sub-basin there is a contrast in basement rock types. For example, Well 83/24-1 drilled metamorphic mudstones of probable Devonian age typical of Gramscatho Basin sedimentary rocks (Evans 1990). Farther south, Well 73/2-1 terminated in >60 m of amphibolite-granulite gneiss with a K-Ar age of 570 ± 10 Ma (Evans, 1990) typical of "Armorican" rocks. We propose that the gneiss in Well 73/2-1 represents upper plate Normannian basement and that in Well 83/24-1 the lower plate.

Normannia has been correlated with the Mid-German Crystalline Rise, a Silurian-Devonian magmatic arc developed on the northern margin of Armorica (Holder & Leveridge 1986b; Franke 2000; Franke *et al*. 2017). The interpretation is consistent with provenance of clasts of Ordovician quartzite (Sadler 1974; Strachan *et al*. 2014), granitoids (Dorr *et al*. 1999) and sandstones (Floyd *et al*. 1991) in the immediately underlying proximal deep marine successions of the Gramscatho Basin. Furthermore, >300 m thickness of Middle Devonian limestone was drilled in Well 87/12-1A, around 50 km SSE of Lizard Point (Evans 1990); these were deposited on Normannian upper plate basement and similar limestones unconformably overlie the Mid German Crystalline Rise in the Saar-1 borehole in Germany (e.g. Franke & Engel 1982; Holder & Leveridge 1986b).

The above data suggest that the leading edge of the upper plate to the Rheic-Rhenohercynian suture in SW England was formed by a continental magmatic arc, developed on Armorican basement, that was active during the Late Silurian and overlain by Middle Devonian carbonates.

Variscan convergence

The sedimentary fill of the Gramscatho Basin was dominated by syn-convergence deposition from the Givetian onwards, associated with southerly subduction of the Rhenohercynian oceanic crust beneath Normannia (e.g. Holder & Leveridge 1986a; Leveridge & Shail 2011b). Progressive deformation, consistent with frontal accretion at the subduction zone, propagated northwards in a series of thrust nappes (Carrick, Veryan, Dodman, Lizard and Normannian) which were emplaced onto the lower plate distal passive margin by the Early Carboniferous (e.g. Wilkinson & Knight 1989). Farther north, deformation in the proximal passive margin was primarily controlled by thick skinned basin inversion (e.g. Leveridge & Hartley 2006; Leveridge 2011). Continent-continent collision lasted until the late Carboniferous culminating in the late Westphalian inversion of the Culm Basin (e.g. Leveridge & Hartley 2006).

In south Cornwall, deformation is marked at outcrop scale by two distinct episodes of folding and cleavage formation (D1 and D2) synchronous with largely co-axial top to the NNW thrusting (e.g. Smith 1965; Rattey & Sanderson 1984; Leveridge *et al.* 1990; Alexander & Shail 1995; 1996). Thrust-related burial metamorphism in the Devonian sedimentary rocks is typically anchizone-epizone (Warr *et al.* 1991); upper greenschist facies metamorphism of the Dodman Nappe supports its development close to the southern active margin of the closing basin (Leveridge 2008). A progressive SSE to NNW younging of D1 cleavage development (385-355 Ma; Leveridge & Hartley 2006) indicates a protracted closure of the oceanic basin. Younger metamorphic ages recorded in North Devon may reflect the culmination of regional D2 deformation around 305 Ma (Leveridge & Hartley 20016). Fluid inclusion analysis of syn-orogenic quartz veins from the Gramscatho Basin indicate several km of exhumation between D1 and D2 (Shail & Wilkinson 1994).

SW England did not reach its current position, adjacent to southern England and Wales, until the end of Variscan convergence in the late Carboniferous (Holder & Leveridge 1986b; Woodcock *et al*. 2007; Leveridge & Shail 2011a). The northern boundary of the Cornubian terrane, as defined by Day *et al*. (1989), can be traced westwards from the Bristol Channel-Bray Fault and beneath the South Celtic Sea Basin; it is represented by significant S-dipping Variscan reflectors identified on deep seismic reflection profiles SWAT 2-3, SWAT 4 and SWAT 5 (BIRPS & ECORS 1986; Day *et al*. 1989).

Extensional reactivation of Variscan structures in the Rheic-Rhenohercynian suture zone

Evidence from field data

Post-Variscan extensional structures are ubiquitous, over a wide range of scales, in coastal outcrops throughout south Cornwall (Shail & Wilkinson 1994). Detailed field analysis has identified a diverse range of structures that are usually kinematically consistent with top-to-the-SSE extensional reactivation of Variscan thrust faults (Alexander 1997). Structures consistently deform D1 and D2 Variscan convergence-related structures developed during top-to-the-NNW thrust-faulting (Alexander & Shail 1995; 1996). There are local variations in the convergence-related deformation chronology, but the extensional structures represent the third episode of regional deformation (D3) (Leveridge & Hartley 2006) and have the following expression:

1) Zones of distributed shear. These are a ductile expression of D3 deformation and comprise F3 folds and S3 cleavage (e.g. Fig. 4a, b) that are best developed in the Mylor Slate Formation, within the parautochthonous footwall of the Carrick Thrust (Leveridge & Holder 1986a; Alexander & Shail 1996). Although complex in areas of high strain, and where subsequent fabric rotation has occurred, these structures typically demonstrate top-to-the-SSE sense of shear (Fig. 5a) (e.g. Alexander & Shail 1995; 1996; Hughes *et al.* 2009).

2) Detachment faults. These are gently- to moderately-dipping bedding or primary cleavage parallel faults that typically indicate a top-to-the-SSE sense of shear (e.g. Fig. 4c and Fig. 5b) consistent with the extensional reactivation of thrust faults (Shail & Wilkinson 1994; Alexander & Shail 1995; 1996). They usually have a brittle-ductile expression; down-dip verging hangingwall folds that may have an associated cleavage and moderately- to steeply-dipping secondary synthetic brittle faults are common. These structures are also most prevalent in proximity to the major thrust faults, e.g. the Carrick and Dodman thrusts of Holder & Leveridge (1986a).

3) Moderate- to high-angle extensional faults. These occur throughout south Cornwall although fault density is variable (e.g. Fig. 4d and Fig. 5b). For example, in the Carrick Nappe, brittle high-angle faults, veins and fractures dominate post-convergence structures and SE- to S-dipping dip-slip faults are dominant (Alexander & Shail 1995; 1996; Alexander 1997). High-angle extensional faults cut kinematically equivalent earlier ductile D3 structures and are compatible with progressive deformation and extensional exhumation.

Palaeostress analyses of the various fault sets demonstrate an episode of NNW-SSE extension on ENE-WSW striking normal faults and sub-ordinate NNW-SSE striking transfer faults (Shail & Alexander 1997). Some faults show evidence of reactivation associated with subsequent intraplate stress regimes which include an episode of Mid-Permian ENE-WSW shortening, followed by Late Permian N-S shortening, and an important Triassic ENE-WSW extensional episode (Shail & Alexander 1997). The timing of reactivation on these faults is supported by cross-cutting relationships and radiometric dating of Early Permian granites and fault-hosted mineralization in Early-Mid Permian and Triassic (e.g. Shail & Alexander 1997; Alexander 1997).

Evidence from geophysical data and offshore sedimentary basins

Field observations from south Cornwall provide a valuable insight into the structural styles and processes active during extensional reactivation of the convergence-related structures in the footwall of the Rheic-Rhenohercynian suture. However, offshore geophysical data provide the opportunity to define the upper plate, that has no clear onshore expression, and interpret the crustal-scale geometries in and adjacent to the reactivated suture zone. The datasets available comprise a regional gravity and magnetic potential field data compilation (Getech 2017) and 2D seismic lines of varying quality acquired for hydrocarbon exploration during the 1970s and 1980s. More recently, WesternGeco acquired and processed several modern 2D seismic lines in 2016-2017, and reprocessed much of the earlier 2D seismic data, as part of an Oil and Gas Authority project to stimulate renewed exploration in the offshore basins of SW Britain. Deep seismic reflection profiles (SWAT lines) acquired in the 1980s (BIRPS & ECORS 1986; Snyder & Hobbs 1999) were also reprocessed in 2017 by WesternGeco; these remain the most useful data for interpreting the crustal-scale geometries of the reactivated suture zone (Fig. 6).

SSE-dipping seismic reflectors have been recognized within the basement of the western English Channel since the 1980s and partially correlated with the trace of onshore thrusts (Day & Edwards 1983; Leveridge *et al.* 1984; Holder & Leveridge 1986a). The development of post-Variscan Permo-Triassic basins throughout *c*. 400 km of the western English Channel and Western Approaches (Fig. 2) is very strongly influenced by the reactivation of the Rheic-Rhenohercynian suture and associated ENE-WSW thrust faults and NNW-SSE transfer faults (Chapman 1989; Day *et al.* 1989; Evans 1990; Hillis & Chapman 1992; Harvey *et al.* 1994; Ruffell *et al.* 1995). Subsidence typically accommodated 3-4 km of Permo-Triassic sediments (Evans 1990) but locally up to 9 km in the Plymouth Bay Basin which is developed above a prominent zone of SSE-dipping reflectors (Harvey *et al*. 1994; Ruffell *et al*. 1995). Early basin evolution is consistent with the extensional reactivation of thrusts and gives rise to a “sag-like” basin with progressive onlap (Fig. 6b, c) during subsidence of the upper plate (e.g. Chapman 1989) or upper plate tilted fault blocks which merge into the reactivated suture (Fig. 6a).

The SSE-dipping reflectors below the northern edge of the Plymouth Bay Basin extend to, and cut, the Moho (Fig. 6c), supporting their interpretation as sutures. To the north is the SW England basement that originally formed the passive margin of the Gramscatho Basin (Fig. 6). Interpretation of the original and reprocessed SWAT lines suggests two sets of southerly dipping reflectors with a block between them (Fig. 6, annotation B) that appears to persist below the basin. The geological significance of this feature remains uncertain since there is no onshore correlation or well penetration. Incoherent reflectivity characterizes the zone immediately overlying and underlying the SSE-dipping reflectors on the northern margin of the basin (Fig. 6, annotation C). We interpret this as the highly deformed Devonian infill of the Gramscatho Basin; high strains are consistent with a position in the immediate hangingwall and footwall of the suture. Field observations from major onshore thrust zones indicate the development of complex fold and thrust geometries, locally steeply-dipping bedding planes and foliation, as well as numerous post-Variscan extensional and strike-slip faults at sub-seismic resolution scale. The varying dips associated with these small- and medium-scale structures, combined with the varying acoustic properties of sandstones, mudstones, olistostromes, limestones and volcanic rocks, are consistent with these zones of incoherent reflectivity.

South of the incoherent reflectivity, a more continuous seismic character is observed within and beneath the post-Variscan basin fill (Fig. 6), some of which can be confidently tied to nearby well control. For example, Well 87/12-1A (50 km SSE of Lizard Point) records over 1200 m of Permian and Triassic red beds overlying a 300 m thick Middle Devonian (Eifelian-Givetian) carbonate package with high acoustic impedance (Evans 1990). The direct well tie and character of the package suggests that it also forms a laterally extensive basement unit beneath the Plymouth Bay Basin (Harvey *et al.* 1994; Ruffell *et al.* 1995). The relative continuity of these reflectors indicates that the upper plate Devonian is comparatively undeformed and similar to the Middle Devonian limestones which overlie Late Ordovician to Silurian granites of the Mid-German Crystalline Rise in the Saar-1 borehole of the Saar-Nahe Basin (Oncken 1997). South of the Lizard Peninsula, Well 86/18-1 drilled 109 m of carbonaceous shales and cherts overlain by Permian to Triassic red beds; Evans (1990) suggested that these carbonaceous rocks could be analogous to "post-orogenic" latest Carboniferous rocks in NW France although an Early Carboniferous or Devonian age was also possible. Details from the stratigraphic log suggest that this succession is also relatively undeformed and horizontally bedded.

At least one major Permian to Triassic unconformity has been recognized within the basin (e.g. Evans 1990) (Fig. 6b, c) and may be controlled by Mid- to Late Permian intraplate shortening episodes (Shail & Alexander 1997). The Lower Jurassic conformably overlies the Triassic but there is an unconformity at the base of Upper Cretaceous Greensand and Chalk that relates to a major episode of late Jurassic to Cretaceous rift-related uplift and exhumation, centred on Cornwall, that was accompanied by Early Cretaceous magmatism e.g. Wolf Rock phonolite 15 km SW of the Land’s End (Evans 1990). Cenozoic contractional inversion structures can also be mapped within the hanging-wall of pre-existing extensional faults (Fig. 6c).

Integration of available gravity and magnetic data (Figs. 7, 8) broadly supports the continuation of the seismically mapped offshore extension of the Dodman Thrust with the northern margin of the Start Complex although this relationship is complicated by a series of steeply-dipping NNW-SSE faults observed onshore and on seismic profiles. There is also a broad correlation between the trace of the suture zone, mapped from outcrop and seismic profiles, and a magnetic low and gravity high marking the northern margin of upper plate Normannia, except in the Melville Basin where salt interferes with the gravity response (Evans 1990).

Early Permian magmatism during extensional reactivation of the suture zone

Lithospheric extension during latest Carboniferous-Early Permian reactivation of the Rheic-Rhenohercynian suture zone was accompanied by exhumation of the lower plate and Early Permian mantle and concomitant crustal partial melting that resulted in *c.* 20 Ma of episodic bimodal magmatism (Chen *et al*. 1993; Shail & Wilkinson 1994; Dupuis *et al*. 2015; Simons *et al*. 2016). Lamprophyre and basalt lavas of the Exeter Volcanic Rocks occur around the base of the lower plate Early Permian successions (Thorpe *et al*. 1986; Edwards *et al*. 1997) and mafic lavas occupy a similar position in the upper plate Western Approaches Basin (Evans 1990; Ruffell *et al*. 1995). Almost 600 m thickness of Lower Permian volcanic rocks have been drilled in the Melville Basin (Well 74/1A-1) and seismic and aeromagnetic data suggest these are laterally extensive and locally up to 3000 m thick (Evans 1990). Extensive partial melting of the lower plate crust, that resulted in the progressive construction of the Cornubian Batholith, was primarily driven by the emplacement of mantle-derived melts (Simons *et al*. 2016).

The chronology of regional D3 extension and basin evolution is partially constrained by radiometric dating of this magmatic activity and the associated mineralization. Steeply-dipping extensional fault zones locally host Early Permian lamprophyre dykes (Alexander & Shail 1996; Dupuis *et al*. 2015). The Cornubian Batholith granites were emplaced in a NNW-SSE extensional regime, based on field observations and AMS analysis of solid-state fabrics in older granites (>289 Ma) and magmatic-state fabrics in all granites (Ghosh 1934; Mintsa Mi Nguema *et al.* 2002; Bouchez *et al.* 2006; Kratinova *et al.* 2010). World-class Early- to Mid-Permian W-Sn-Cu magmatic-hydrothermal mineralization is typically hosted by ENE-WSW to E-W striking high-angle extensional fault zones developed during ongoing NNW-SSE crustal extension (Willis-Richards & Jackson 1989; Chen *et al*. 1993; Shail & Wilkinson 1994; Shail *et al*. 2003).

Implications of geophysical observations for the Rheic-Rhenohercynian Suture

The predominance of S-dipping crustal reflectors extending to, and through, the Moho on the northern margin of the Western Approaches Trough and Plymouth Bay Basin is consistent with southwards subduction of the SW England distal passive margin beneath Normannia (e.g. Holder & Leveridge 1986a; Le Gall 1990; Shail & Leveridge 2009). The interpretation of two parallel S-dipping reflection events approximately 25 km apart beneath the Moho (Fig. 6c) indicate distinct packages of contrasting acoustic impedance within the lithospheric mantle. Following the model proposed for closely-spaced Rheic and Rhenohercynian ocean sutures in the Northern Phyllite Zone of Germany (Franke 2000; Franke *et al*. 2017), one possibility is that the northern reflectors represent a late Silurian Rheic Ocean suture and the southern reflectors a Rhenohercynian (Lizard) Ocean suture. The co-occurrence of proximal southerly-derived Silurian and Late Devonian magmatic arc detritus within the Devonian Gramscatho Basin (Dorr *et al.* 1999) cannot be easily explained by closure of a single Devonian Rhenohercynian Ocean. Therefore, subduction and collision associated with an older Rheic Ocean segment must have occurred in the vicinity.

Although there are indications of mid-crustal N-dipping reflectors beneath the Plymouth Bay Basin (SWAT lines 8 and 9, Fig. 6) there is no evidence for associated S-verging folds and thrusts in this part of the Variscan Orogen or along strike in continental Europe (e.g. Franke 2000). This package most likely reflects a primary lithostratigraphic boundary between Upper Paleozoic successions and Normannian basement; it is clearly truncated by the younger, S-dipping reflectors.

The predominance of southwards-dipping mantle reflectors is difficult to reconcile with models, proposed on the basis of subduction-related volcanism and ore formation, where the Rhenohercynian Ocean formed in a retro-arc setting associated with northwards subduction of the Rheic Ocean (e.g. Eckelmann *et al.* 2014; von Raumer *et al.* 2016). A model of the Rhenohercynian Ocean as a late-formed basin is preferred, opening around the site of a closed central Rheic Ocean segment, possibly reactivating earlier convergence-related structures (Fig. 9). Rifting of passive margins opposite active subduction zone is not atypical and is, for example, characteristic of the mode of closure of Palaeo-Tethys synchronous with opening of the Neo-Tethys (e.g. Robertson 2007).

The gravity and magnetic anomaly data from the study area, and its comparison with equivalent data in Germany and NE France, is also pertinent to the positioning of the Rheic and Rhenohercynian sutures (e.g. Edel & Schulmann 2009; Gabriel *et al.* 2011). In Germany, prominent NE-SW positive magnetic anomalies in the Mid-German Crystalline Rise are subparallel to the mapped tectonic boundaries in the east but divergent in the west, perhaps implying some degree of obliquity during convergence (e.g. Edel & Schulmann 2009). These anomalies have been interpreted to represent mid- or upper crustal features given their varied wavelength (Gabriel *et al.* 2011). In the Vosges Mountains, these features are also correlated with the Mid-German Crystalline Rise magmatic arc (Edel & Schulmann 2009). This pattern is geometrically similar to and therefore potentially correlatable with the magnetic and gravity lineaments and anomalies of the western English Channel and Channel Basin approximately parallel to the UK-French maritime border (Fig. 7, 8). Nevertheless, some anomalies could be correlated with local Early Permian volcanic packages revealed by offshore drilling such as in the southern part of the Melville Sub-basin (Evans 1990) and postulated in the Plymouth Bay Basin (Harvey *et al.* 1994; Ruffell *et al.* 1995). The large positive magnetic anomalies could correspond to the Normannian magmatic arc; the magnetic high approximately 60 km SE of Start Point (Fig. 7) appears truncated on its northern margin by an E-W fault zone. Seismic calibration of this magnetic high, combined with its short wavelength, suggests that it is a relatively shallow basement feature beneath the post-Variscan basins. In the Channel Basin, these magnetic anomalies and gravity lineaments have been correlated with the Rheic-Rhenohercynian suture, which merges with the NW-SE Bristol Channel - Bray Fault (Fig. 2) and farther south diverges from the Paris Basin Magnetic Anomaly into the westward extension of the Mid-German Crystalline Rise and Saxothuringian Zone (Holder & Leveridge, 1986b; Busby & Smith 2001; Averbuch & Piromallo 2012). Isostatic residual gravity data in the study area (Fig. 6) are dominated by marked negative gravity anomalies associated with the Cornubian Batholith stretching from Dartmoor in the east almost to the continental shelf via the Isles of Scilly granites; the low gravity values are repeated to the north around the Haig Fras Batholith. Overall, the granites are emplaced into a broad zone with a relatively high gravity signature trending ENE-WSW.

Whilst there is no definitive magnetic and gravity signature associated with the Northern Phyllite Zone which contains the Rheic and Rhenohercynian Sutures in Germany (Oncken 1997; Franke *et al*. 2017), magnetic and gravity lineaments are broadly parallel to the geologically mapped trace of this zone and extend for several hundred kilometres (e.g. Edel & Schulmann 2009; Gabriel *et al.* 2011). These have similar characteristics to low magnetic anomalies that extend westwards from the Start Complex towards Dodman Point (Fig. 7) which substantiates earlier correlation with the Northern Phyllite Zone (Holder & Leveridge 1986a, b).

A prominent feature of the magnetic and gravity data is the change from ENE-WSW trends in the south and west to E-W trends in the east and north. The magnetic anomaly data (Fig. 7) support an eastwards continuation of ENE-WSW trends into the English Channel and westwards towards the South Celtic Sea. Onshore, the boundary between these different trends corresponds to steeply dipping high strain primary and secondary fabrics that define the Start–Perranporth Zone (Fig. 3). It has been interpreted as a terrane boundary separating Avalonia from Armorica (Holdsworth 1989). A Devonian terrane boundary interpretation has been challenged due to the continuity of Early Devonian sedimentation (Leveridge & Hartley 2006). The steep fabrics are alternatively considered to result from backfolding, during top-to-the south extensional reactivation (D3), of a major out-of-sequence high strain D2 thrust zone, aided by forced folding above a former passive margin bounding fault on the northern margin of the Gramscatho Basin (Shail & Leveridge 2009).

Synthesis and tectonic model

The Rheic Ocean was the major ocean separating Gondwana from Laurussia but, given the number of candidate sutures described across the Variscan Orogen, it was more likely to have comprised a series of evolving oceanic basins, much like the Mesozoic-Cenozoic Tethys Ocean (e.g. Robertson 2007; Murphy *et al*. 2016). SW England lithosphere was near opening oceans during the: (1) Early Ordovician (Rheic Ocean), and (2) Early Devonian (Rhenohercynian Ocean). The closure of these oceans resulted in the Rheic-Rhenohercynian suture zone and Variscan orogen.

This study confirms the observations of Edel & Schulmann (2009) that existing geophysical data support only southwards Devonian subduction between the Rhenohercynian and Saxothuringian zones. No geological or geophysical evidence supports a N-dipping Devonian subduction zone in the study area. There is geological and geophysical support for the pre-Devonian closure of a northern Rheic Ocean segment and creation of the successor Rhenohercynian Ocean (Franke 2000; Shail & Leveridge 2009; Franke *et al*. 2017). A synthesis of the evolution and reactivation of suture zones during the Early Silurian to Early Carboniferous, is presented in Fig. 9.

1. A northern segment of the Rheic Ocean, developed during Cambrian-Ordovician rifting of the Gondwana margin, separated Avalonia from SW England (Armorican basement affinities), and closed by the latest Silurian by N-dipping subduction beneath Avalonia (e.g. Woodcock *et al*. 2007; Shail & Leveridge 2009; Dijkstra & Hatch 2018) (Fig 9). This corresponds to the northern dashed line overlain on the magnetic and gravity compilations (Figs. 7, 8).

2. A central segment of Rheic Ocean also formed during Cambrian-Ordovician rifting, and separated SW England from Normannia (correlated with the Mid-German Crystalline Rise, Léon Domain and Saxothuringia). It may have closed by the earliest Devonian (Model 2a) or Late Devonian (Model 2b), by southwards subduction beneath Normannia (Fig 9). A tentative surface position of this segment suture is illustrated as the central dashed line on Fig. 7 and Fig. 8.
3. A southern segment of the Rheic Ocean (correlated with the Saxothuringian Ocean, Tepla Suture, Le Conquet Suture, Léon Sea) separated the Normannian Terrane from Armorica (Figs. 7, 8). It formed during the Cambrian-Ordovician, remained relatively narrow throughout the Silurian and closed during the Devonian by southwards subduction beneath Armorica and Moldanubia (Fig 9).
4. The combined width of the these three Rheic Ocean segments may have reached *c.* 4000 km during the Silurian (e.g. Domeier 2016).
5. The Rhenohercynian Ocean formed during the Early Devonian, either at the site of the late Silurian closure of the central Rheic segment (Model 2a), or by rifting of a continental ribbon fragment from the southern margin of SW England during ongoing subduction of the central Rheic segment (Model 2b – not shown).
6. Southwards subduction of the Rhenohercynian Ocean beneath Normannia began in the late Middle Devonian (Givetian) and had ceased by the latest Devonian or earliest Carboniferous. It resulted in the composite Rheic-Rhenohercynian suture.
7. Variscan convergence continued throughout much of the Carboniferous and final juxtaposition with southern Britain occurred along the Bristol Channel-Bray Fault Zone.
8. Latest Carboniferous to Early Permian lithospheric thinning was primarily controlled by extensional reactivation of the Rheic-Rhenohercynian suture and associated thrust faults. It resulted in the early development of the Western Approaches basins in the hangingwall of the suture and generation of substantial mantle- and crustally-derived melts and accompanying magmatic-hydrothermal W-Sn-Cu mineralization (Cornubian Batholith) in the exhumed footwall.

As originally recognized by Wilson (1966), the North Atlantic Ocean opened sub-parallel to the Caledonian (Iapetus) suture and thrust belts to the north of the Variscan Front and both the Caledonian and Variscan (Rheic) suture to the south of the Bay of Biscay (e.g. Chenin *et al.* 2015). However, the North Atlantic cut across the structural grain in between. Chenin *et al.* (2015) proposed that the major (>2000 km wide) oceanic sutures were reactivated whilst the smaller (<1000 km wide) oceanic basins (e.g. Rhenohercynian) were not. However, our observations suggest that there was an earlier episode of significant extensional reactivation of the Rheic-Rhenohercynian suture zone immediately after Variscan convergence (late Carboniferous to Early Permian). The failure to progress to another ocean was due to a change in plate boundary stresses towards the end of the Early Permian (Edel *et al.* 2018). Analysis of post-Variscan fault systems in Cornwall indicates that Early Permian extension gave way to intraplate shortening events in the Mid-Late Permian (Shail & Alexander 1997) and that this may explain major unconformities and hiatuses in the Permian successions (e.g. Edwards *et al.* 1997).

Conclusions

Integrated analysis of the lower and upper plates of the composite Rheic-Rhenohercynian suture zone from onshore field and offshore geophysical data has provided an insight into its evolution during Variscan convergence and post-Variscan extensional reactivation.

- The Rheic Ocean most likely comprised three evolving oceanic basin segments between Avalonia and Armorica.
- The central segment of the Rheic Ocean, separating SW England and the Normannian Silurian magmatic arc (a lateral equivalent of the Mid-German Crystalline Rise), was probably achieved by southwards subduction the latest Silurian

- Opening of the Rhenohercynian Ocean in the Early Devonian occurred close to the site of the central Rheic suture. Closure of the Rhenohercynian Ocean was achieved by southwards subduction and accretion against a Normannian Devonian magmatic arc during the Upper Devonian.
- Field evidence from south Cornwall demonstrates post-convergence NNW-SSE extensional reactivation of Variscan convergence-related structures in the footwall (or lower plate) of the composite Rheic-Rhenohercynian suture during the latest Carboniferous to Early Permian. The Western Approaches Basin occurred synchronously with this extensional reactivation of the Rheic/Rhenohercynian suture zone as predominantly upper plate "sag-like" basins. Extension was synchronous with the generation and emplacement of mantle-derived (lamprophyres/basalts) and crustally-derived (granite) magmas in the lower plate and extrusion of mantle-derived lavas into upper plate sedimentary basins.
- SW England and the surrounding offshore sedimentary basins provides a superb example of extensional reactivation of suture zones as predicted in the Wilson Cycle and includes Devonian rifting and oceanic basin formation, Late Devonian to Carboniferous convergence and collision and latest Carboniferous to Permian extensional reactivation and basin evolution.

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Figures and captions

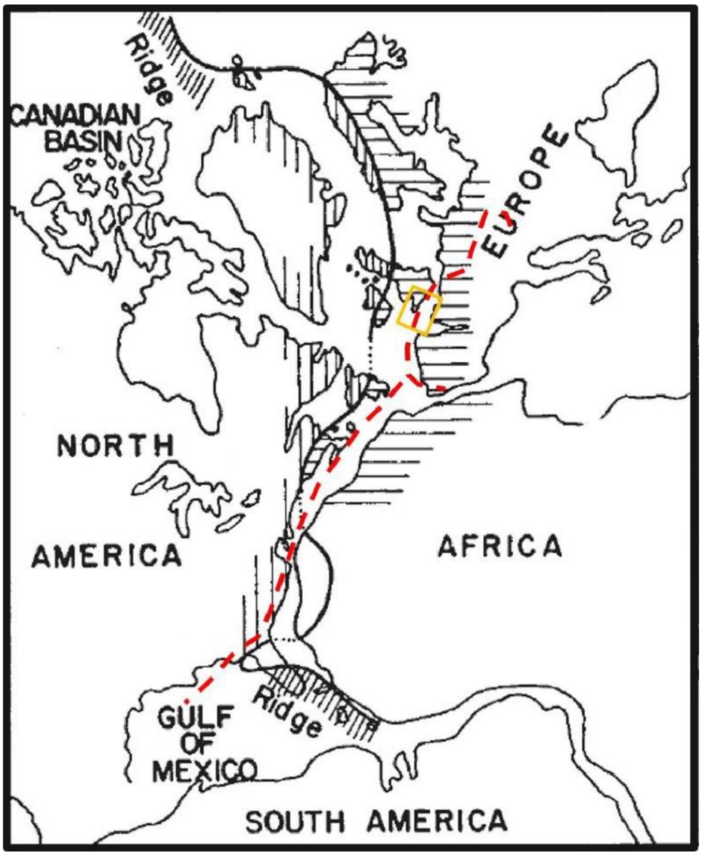


Fig.1. Wilson (1966) North Atlantic reconstruction with the Rheic Suture overlay in red (from Nance *et al*. 2012). The present study area is within the orange box.

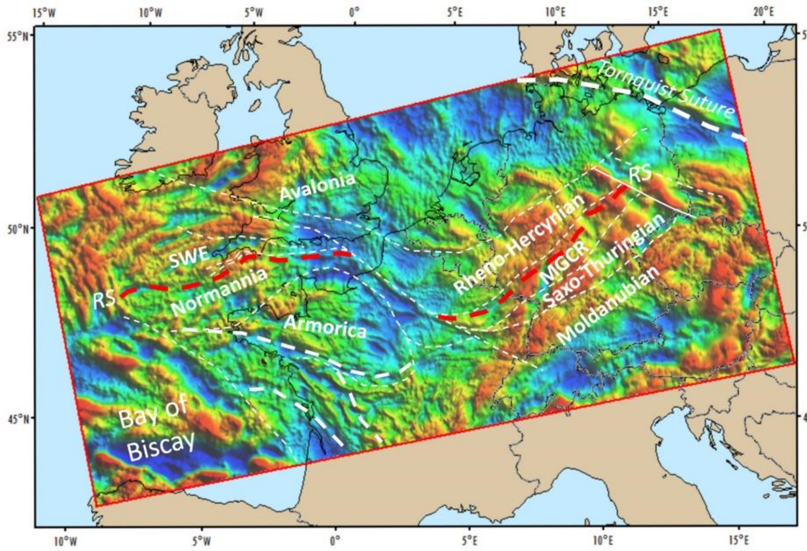


Fig. 2. Simplified tectonic zones and sutures of NW Europe, based on previous compilations (Edel & Schulmann 2009; Nance *et al*. 2010; Edel *et al*. 2013; Kroner & Romer 2013; Franke 2000; Franke *et al*. 2017 and references therein) overlain on the regional gravity compilation of Getech (2017). Key regional features include a typical location for the Rheic Suture Zone (RS), MCGR – Mid German Crystalline Rise, SWE- SW England, Rhenohercynian – Rhenohercynian Zone, Saxothuringian – Saxothuringian Zone, Moldanubian – Moldanubian Zone. The study area encompasses the area of SW England (representing the Lower Plate) and Normannia (representing the Upper Plate).

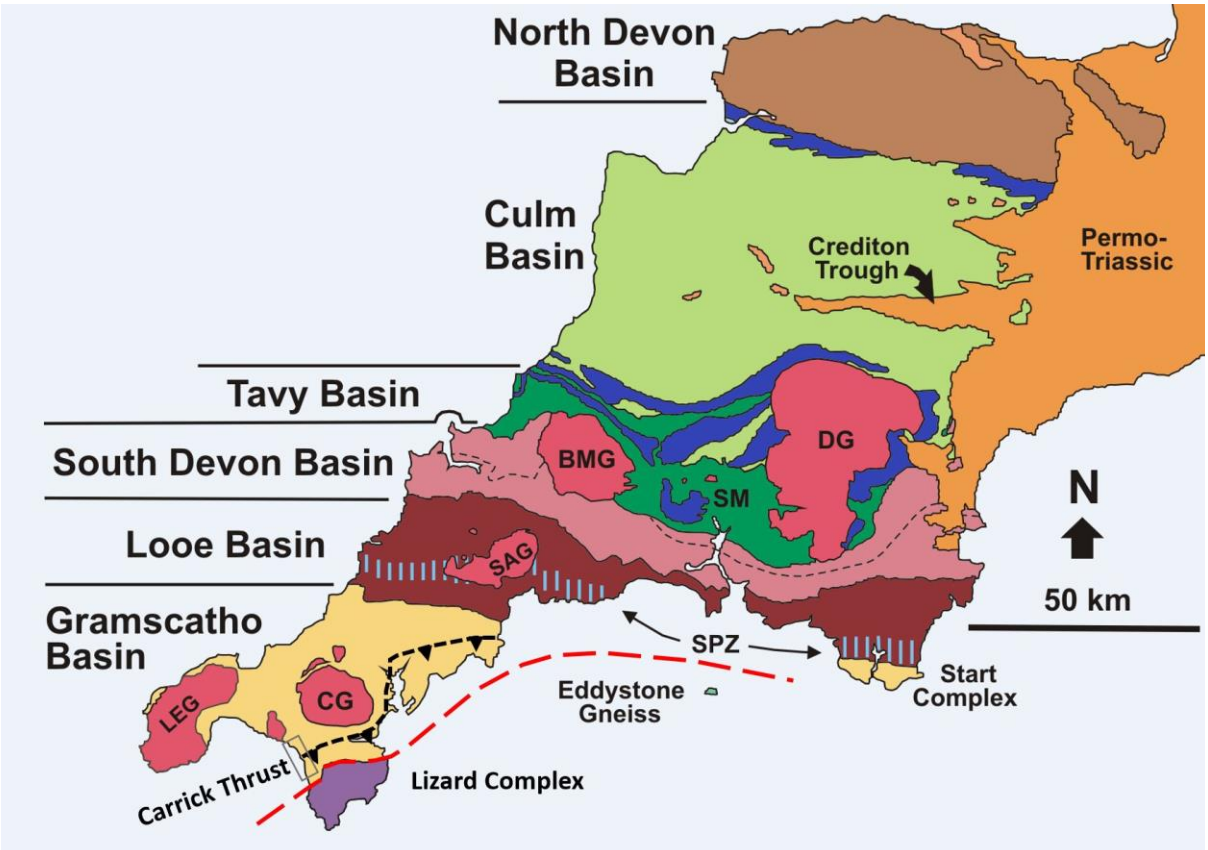


Fig. 3. Tectonic map of SW England modified from Shail & Leveridge (2009) showing the main basins referred to in the text forming the lower plate of the Rheic-Rhenohercynian suture to the north of the red dashed line. The example structures in Fig. 4 are exposed in the area denoted by the grey box spanning the footwall and hanging-wall of the Carrick Thrust. The granites are labelled as following: LEG – Land's End, CG – Carnmenellis Granite, SAG – St. Austell, BMG – Bodmin Moor, DG – Dartmoor. The St. Mellion klippe and Start-Perranporth Zone are labelled as SM and SPZ respectively. Reproduced from Shail, R.K. & Leveridge, B.E. Comptes Rendus Geoscience, 2009, 341, pp. 140–155

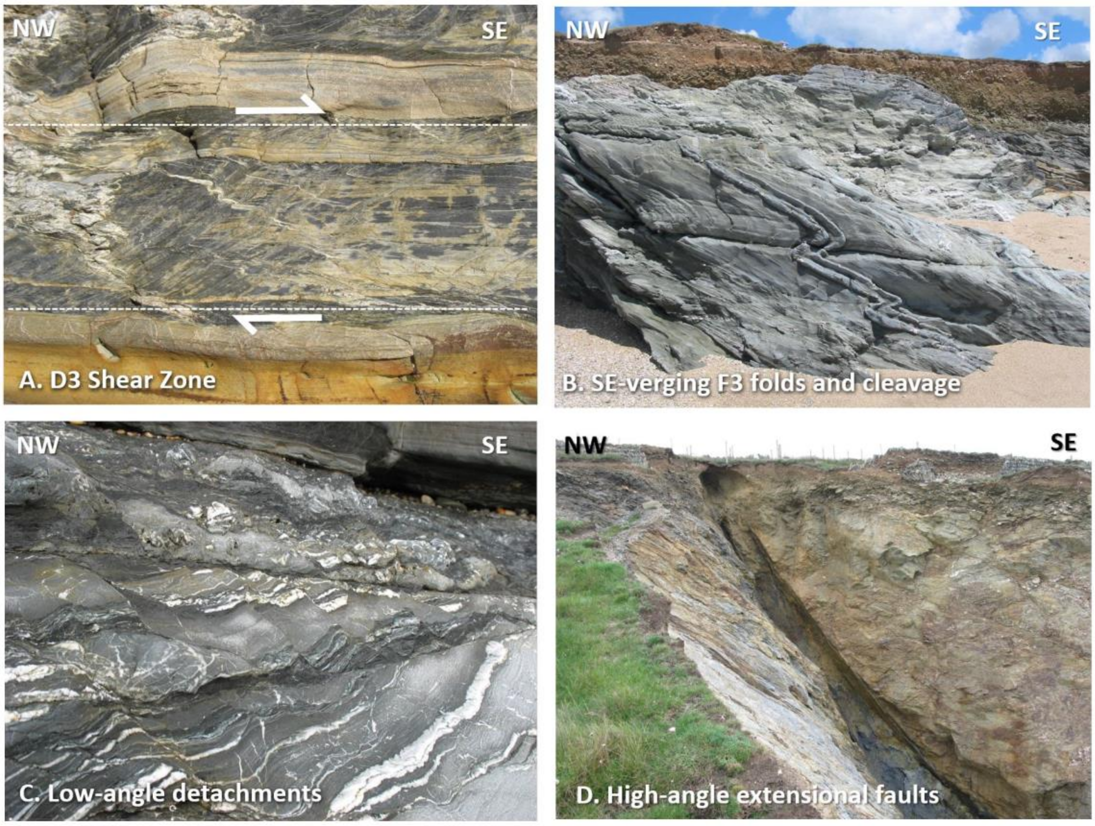


Fig. 4. Field photographs of examples of the main D3 deformation styles from Porthleven Beach, south Cornwall. (**a**) shows a minor bedding parallel ductile D3 shear zone deforming earlier contractional fabrics. (**b**) shows southeast verging F3 folds with subhorizontal axial planar cleavage deforming bedding and D1 fabrics. These ductile structures occur only in the footwall of the Carrick Thrust between Porthleven and Loe Bar. (**c**) shows an example low angle detachment fault showing top to the southeast sense of displacement. These structures are common near the Carrick Thrust trace. High angle faults such as in (**d**) occur throughout the section but are particularly prevalent to the south of section.

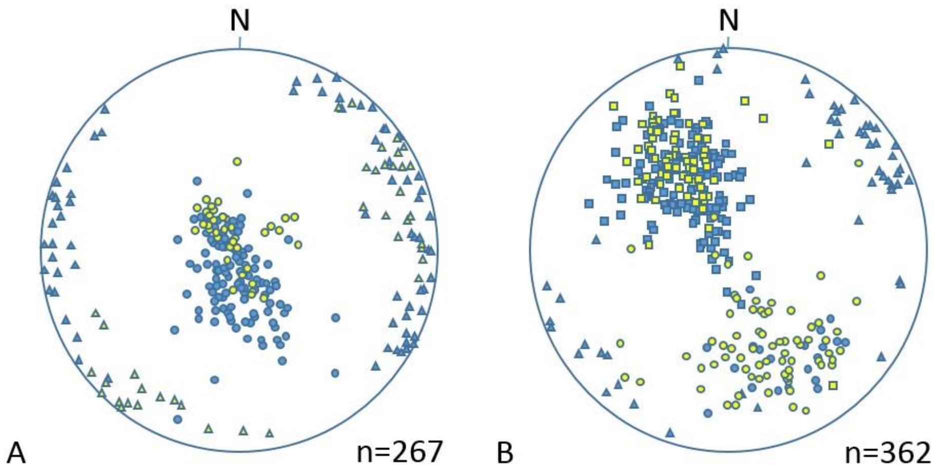
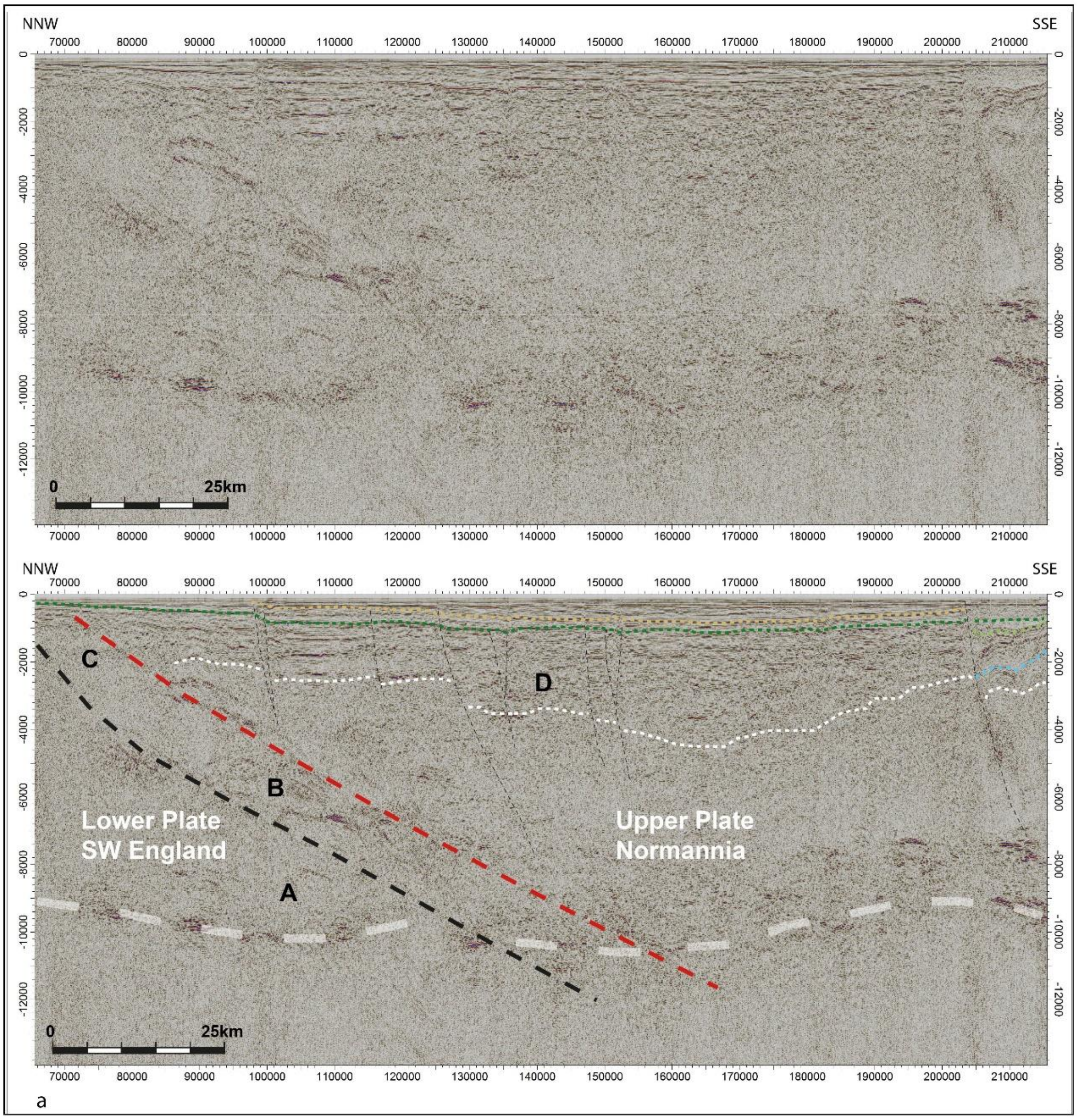


Fig. 5. Compilation of a subset of D3 data from the north coast of South Cornwall (blue) and from the south coast (yellow). (**a**) shows poles to S3 cleavage as circles and F3 fold axes as triangles from zones of distributed shear. (**b**) shows poles to major early D3 faults and detachments as squares with slickenline pitch displayed as circles and associated F3 fold axes denoted as triangles.

Fig. 6 (next three pages). Deep crustal SWAT lines from the Plymouth Bay Basin and St. Mary's Basin (BIRPS & ECORS 1986, Snyder & Hobbs 1999). Locations shown in Fig. 7,8. (**a**) SWAT6-7 from the St. Mary's Basin, (**b**) is SWAT9 and (**c**) is SWAT8 both from the Plymouth Bay Basin. Vertical scale is in TWT (ms). The large dashed lines mark the Moho. The south-dipping dashed lines mark potential suture zones with the northern black line interpreted as an earlier Rheic Ocean suture separating lower plate SW England (Annotation A) from assumed segments of Normannia (Annotation B). The southern red dashed line is an interpretation of the younger Rhenohercynian Ocean suture separating lower plate SW England (Annotation A, B) from the upper plate Normannia. This suture sub-crops a short distance south of the Lizard, Dodman and Start Points. In (c) these events clearly extend below the Moho. Annotation C illustrates the area of low reflectivity "noise" probably because of high strain deformation in the immediate footwall of the Rhenohercynian suture zone. The Variscan unconformity is interpreted at the dashed white line and forms the base of post-Variscan latest Carboniferous to Triassic basin fill. In the Plymouth Bay Basin a package of high impedance reflectors marked in red is interpreted as extrusive volcanic rocks age equivalent with the granites in the lower plate. A significant intra-Permian unconformity is marked as a purple dashed line where observed clearly. The approximate base of the Jurassic is marked in pale blue and is locally preserved in inherited Jurassic graben features which were subsequently partially reactivated during regional Early Cretaceous uplift and exhumation which generated a significant unconformity overlain by rocks as old as Aptian. The interpreted base of the Upper Cretaceous is marked in green and the base Cenozoic in pale brown. Cenozoic structural reactivation can be observed in Fig. 6c.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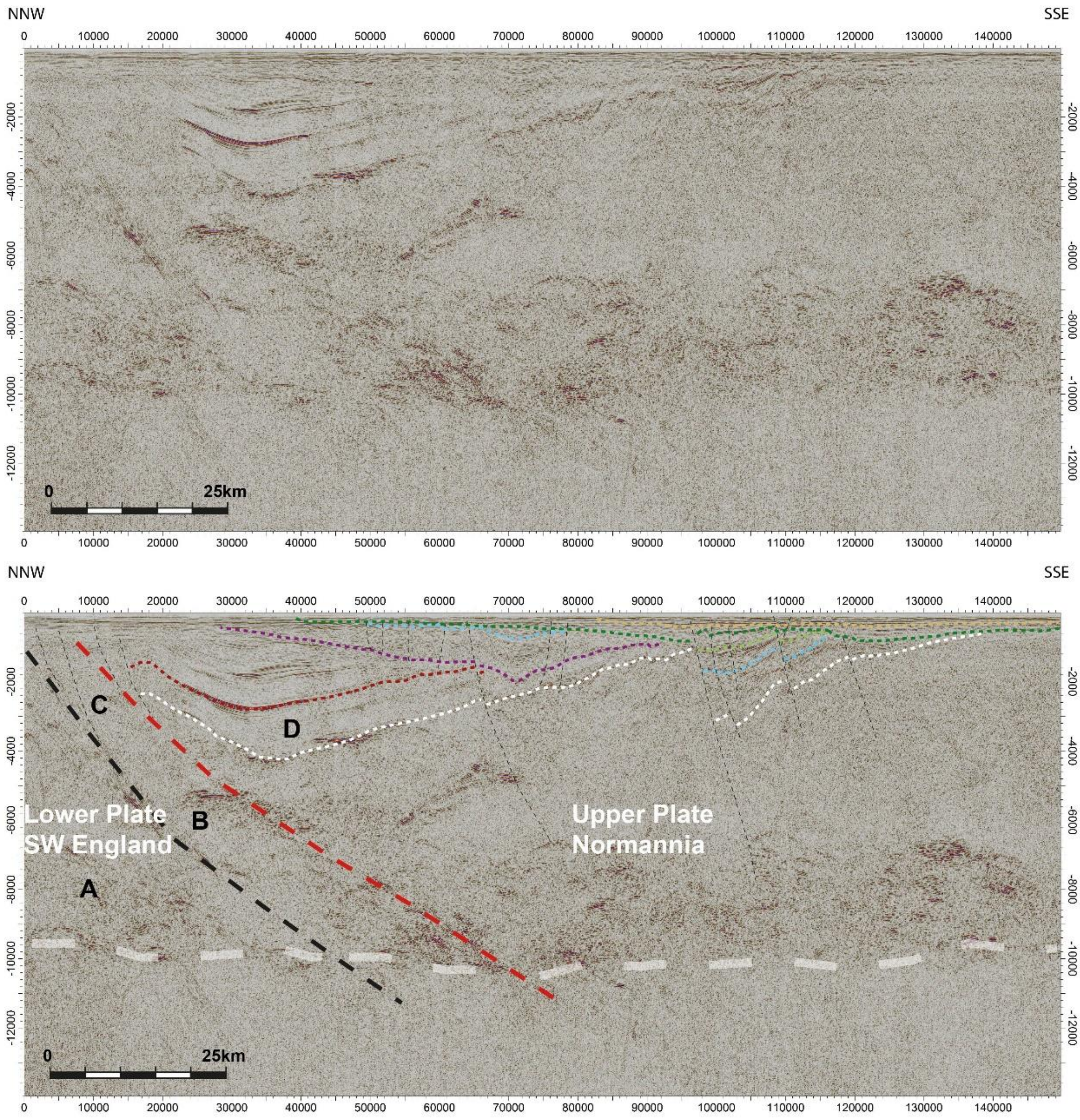
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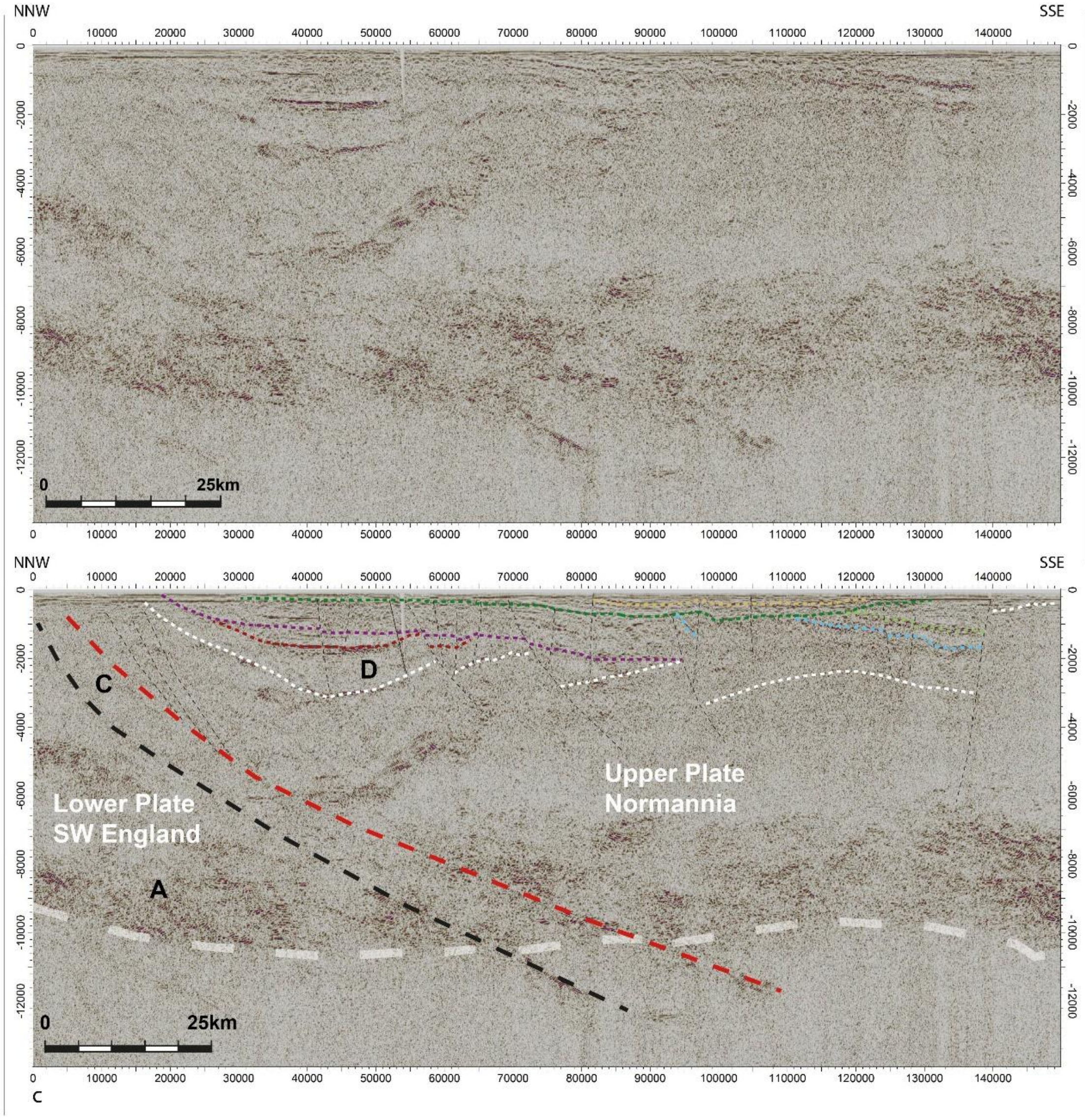
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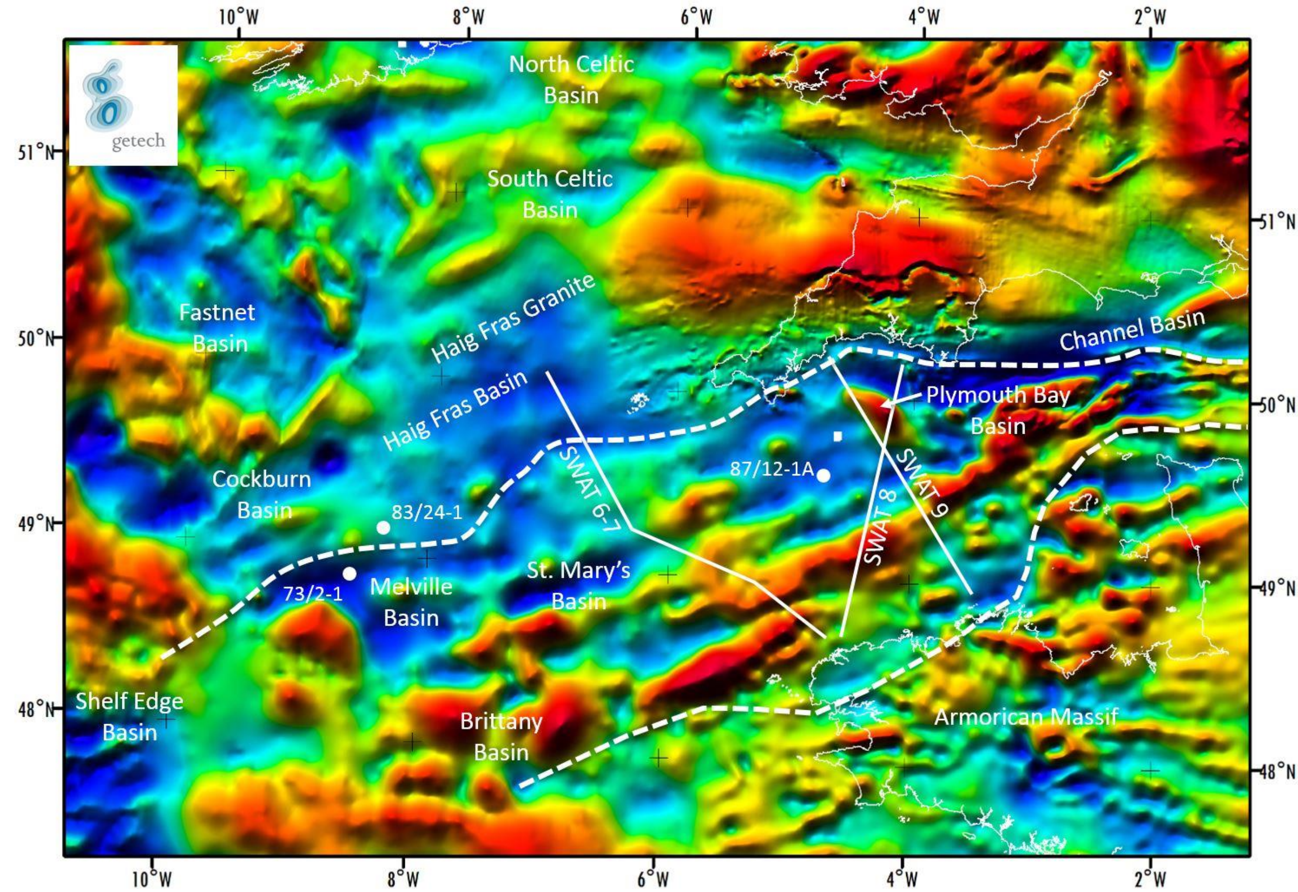

Fig. 7. Total magnetic intensity data compilation from the study area (courtesy of Getech). Seismic lines and the wells mentioned in the text are also highlighted. The dashed lines correspond to the Northern Segment Rheic Suture (Dijkstra & Hatch 2018), Central Segment Rheic-Rhenohercynian Sutures and Southern Segment Rheic Suture from north to south as described in the text.

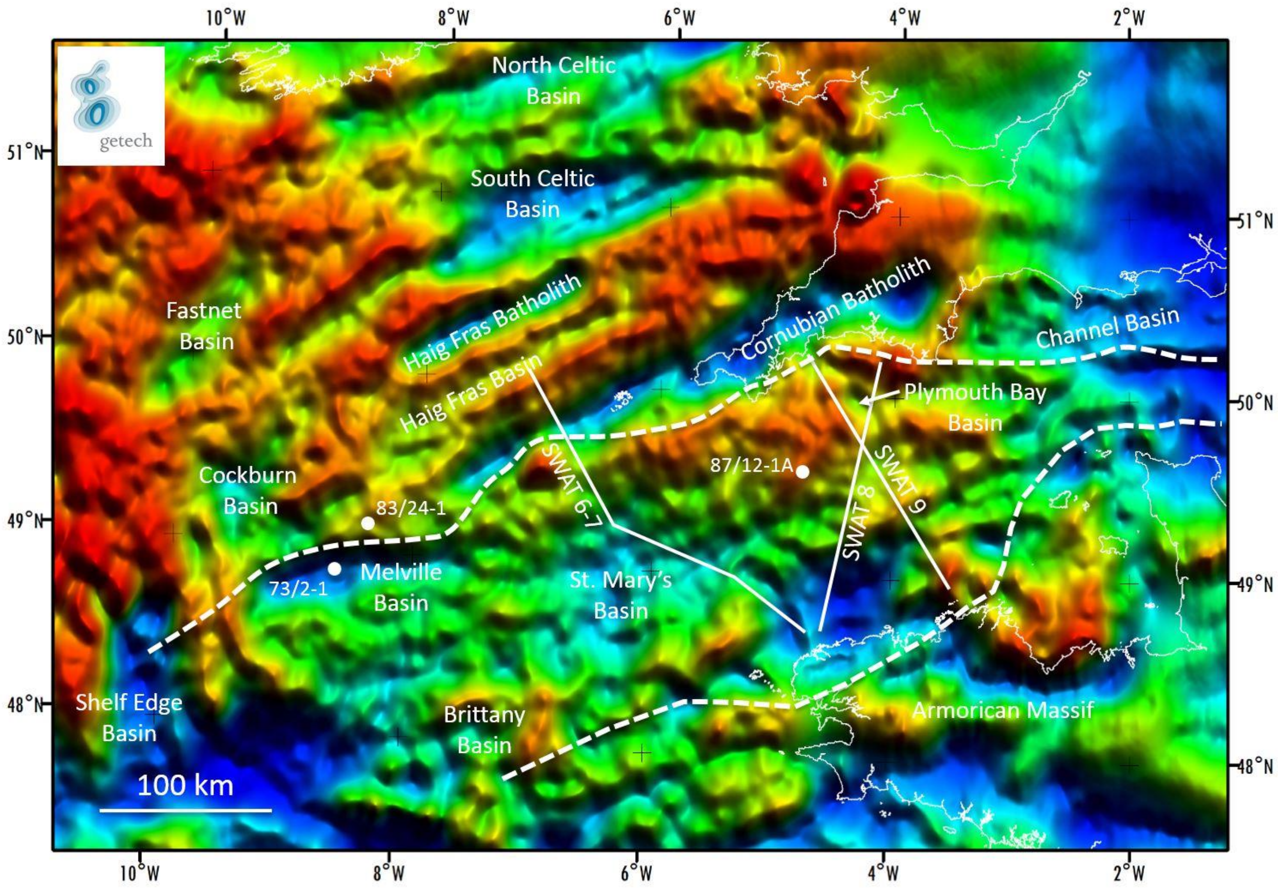

Fig. 8. Isostatic residual gravity data compilation from the Study Area showing the main features (courtesy of Getech). Seismic lines and the wells mentioned in the text are also highlighted. The sutures are identified as in Fig. 7.

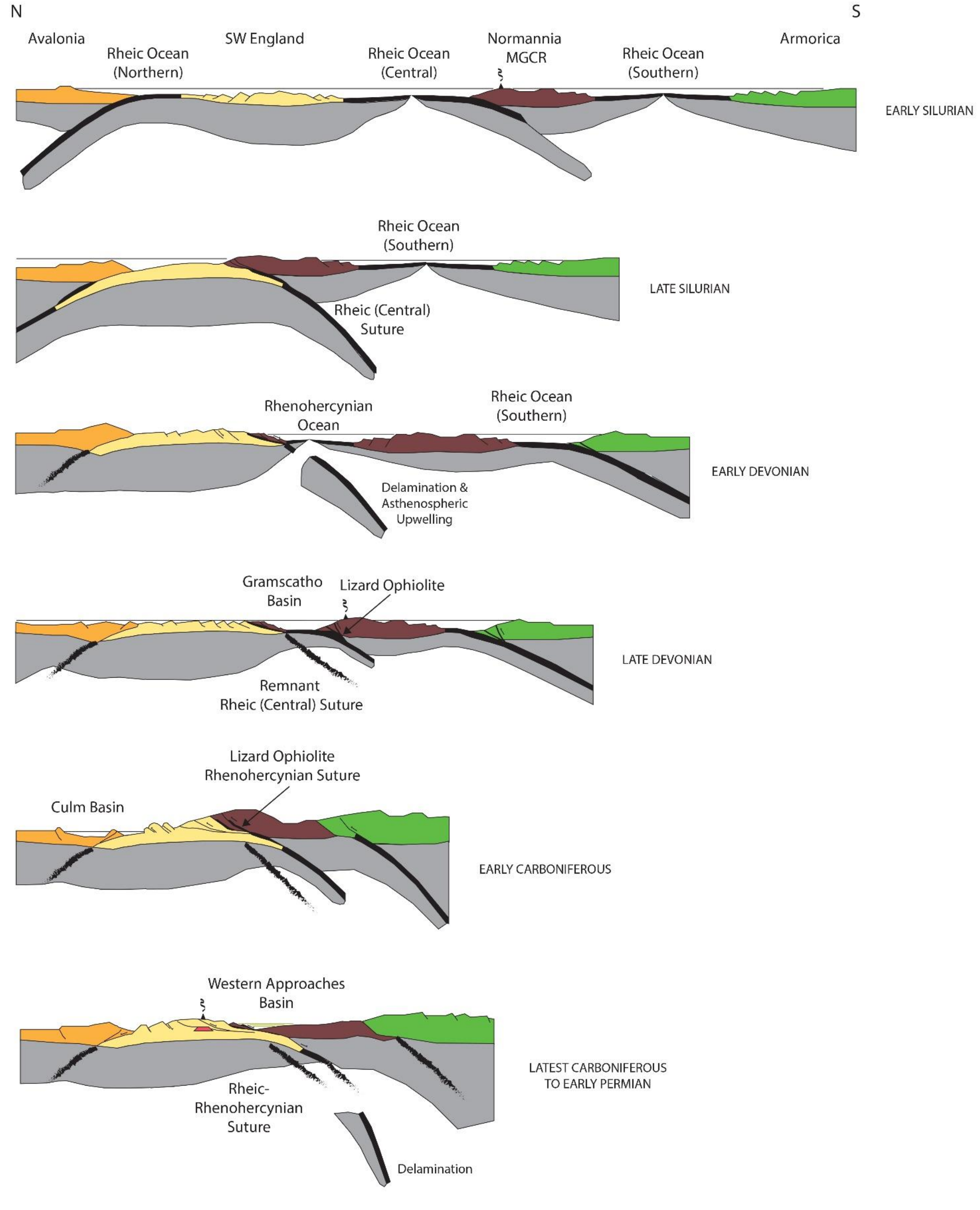

Fig. 9. Preferred plate tectonic synthesis following some modifications from Shail & Leveridge (2009) from Silurian to Permian. This model involves an early closure of the northern (Dijkstra & Hatch 2018) and central Rheic Ocean segments in the latest Silurian and subsequent opening of Rhenohercynian Ocean as a successor basin (Early Devonian) in a similar location perhaps reactivating the former suture. An alternative model allows the Rheic Ocean to remain open while the Rhenohercynian Ocean forms on SW England basement. Both models imply only southwards directed subduction to the south of SW England. Final closure occurs in the Late Devonian to Carboniferous followed by significant extensional reactivation in the latest Carboniferous to Permian. Note that there is reactivation of major boundaries during the Mesozoic and Cenozoic which is not captured in this summary.